CRASTE 2016: Reducing Cost, Increasing Safety

Mid-Air Retrieval of Heavy, Earth-Returning Space Systems

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Mid-Air Retrieval Background

NASA Technology Need

- NASA 2015 Technology Roadmap
  - TA 9: Entry, Descent, and Landing Systems
    - TA 9.3: Landing
      - TA 9.3.1: Propulsion and Touchdown Systems

        Benefits of Technology

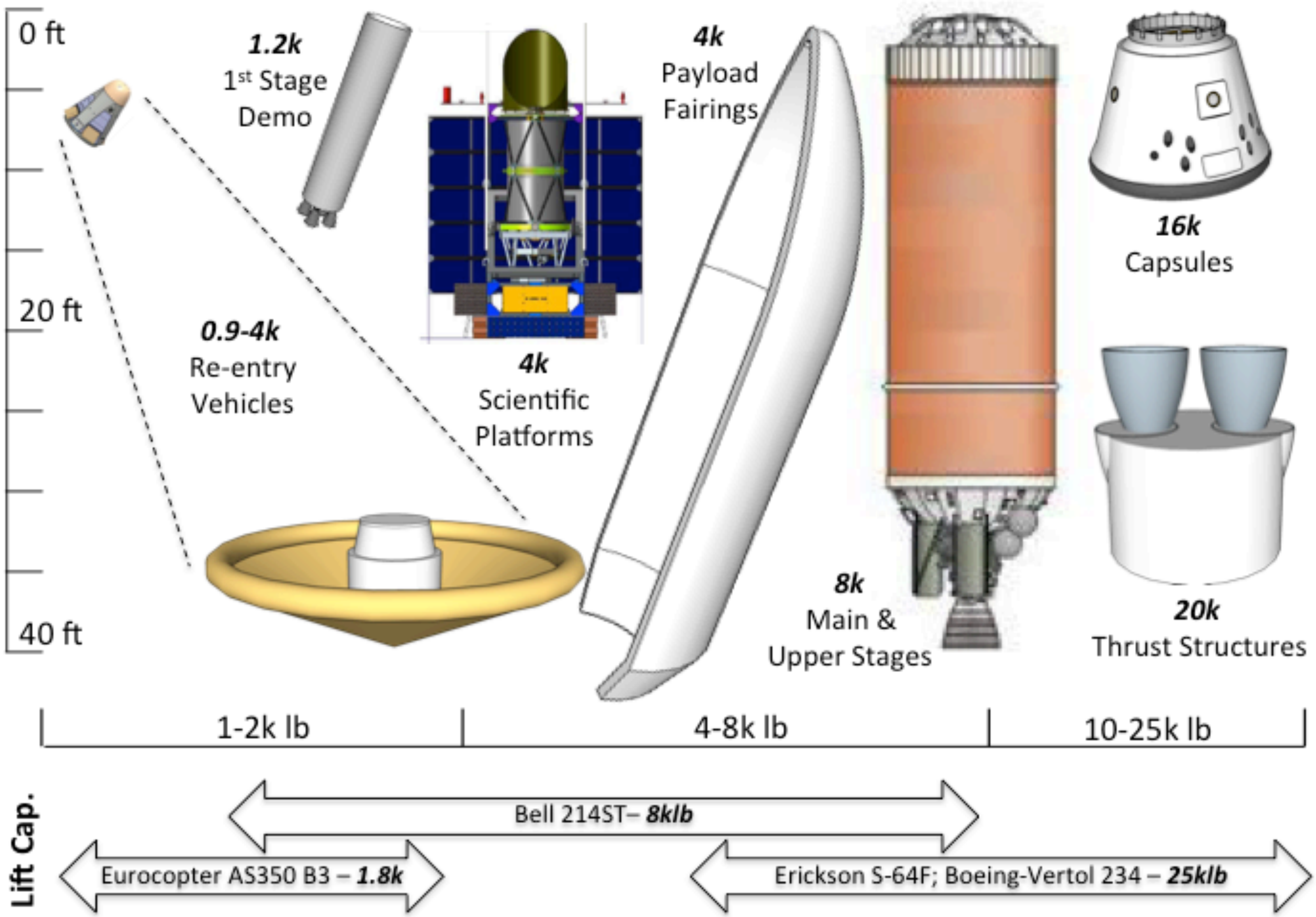
        Improved touchdown systems will increase access for NASA science missions and improve reliability for NASA human missions to the Moon, Mars, or other bodies. Alternative options such as mid-air retrieval at Earth could lower the cost and expand the reusability of the architectural elements to achieve these missions.

        » 9.3.1.3: Mid-Air Retrieval (MAR)

        Capability Description: This capability recovers objects in Earth's atmosphere, before they impact the ground. Uses include: sensitive payloads that cannot survive a shock impact; payloads that must be kept secure; items that need to be returned to a specific location more quickly than they can be located, accessed, and transported after landing; and high-value hardware that can be reused with minimal refurbishment, to save costs.

http://www.nasa.gov/offices/oct/home/roadmaps/index.html

Notional MAR Opportunities



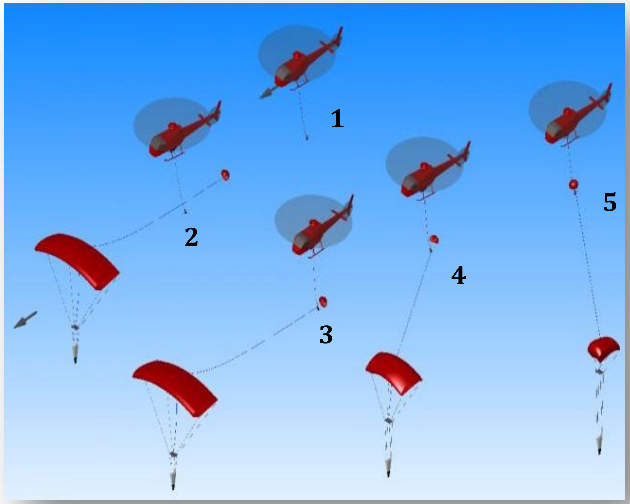
Historical Perspective

- Mid-air retrieval of small payloads is not a new concept

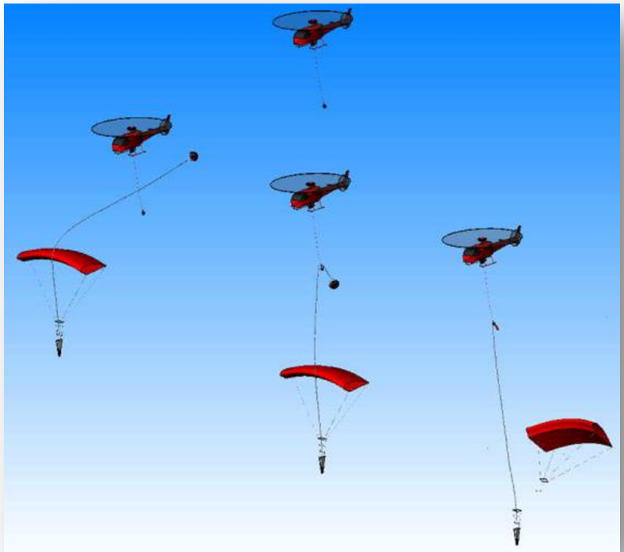
Date	Project / Vehicle	Recovery Aircraft	Summary
1955	AQM 34 Firebee (USAF)	Military (C-119)	Target drone recovery
1956	Operation Genetrix (USAF)	Military (C-119)	Balloon launched reconnaissance payload recovery
1956-83	High Altitude Sampling Program (Project Ashcan) (USAF/NASA)	Military (C-119, C-130)	Balloon launched sample container recovery
1960-72	Discoverer (Corona) (USAF)	Military (C-119)	Satellite film canister recovery
1964-75	Mode 147 Lightning Bug (USAF)	Military (CH-3)	Reconnaissance drone recovery
2004	Project Genesis (NASA)	Civilian (Eurocopter Astar 350-B2)	Sample container recovery

3rd Gen MAR and its Advantages

- Commercial context
- Commercially available aircraft
- No aircraft modifications or “experimental” classification required
- Low-speed, low-g pick-up
  - Easy on helicopter and payload; 0.2g demonstrated
  - Matched speed for precise pick-up
- Limited training required
  - Corona missions spent $100M (in 2015 dollars) on training



MAR with Parafoil Collapse


MAR with Parafoil Release

Heavy-Lift Mid-Air Retrieval Study

NASA Heavy-Lift MAR Study

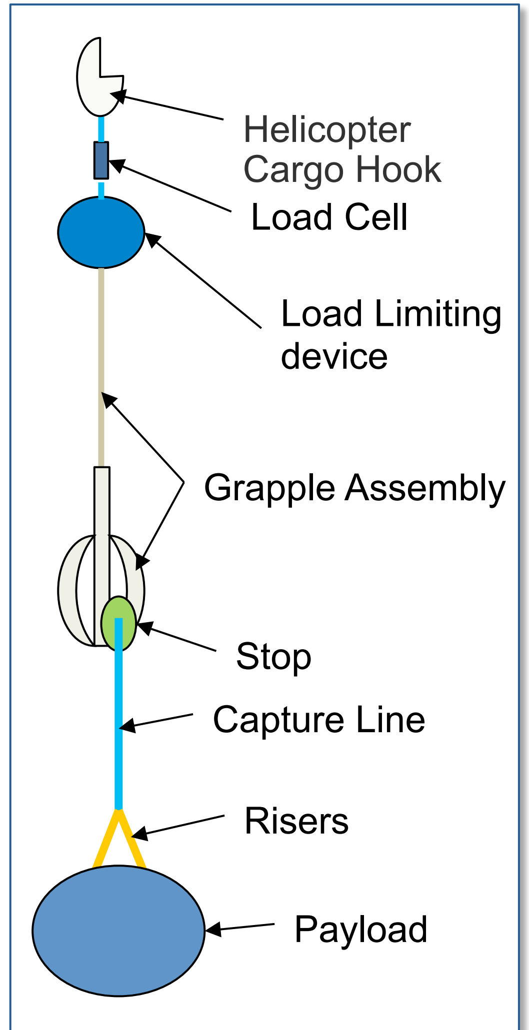
- Initiated a small study under NASA Space Technology Mission Directorate's Center Innovation Fund (nom. $100k, 0.5 FTE)

- **Study Scope:**

1. Aero-mechanical systems study
   - Develop a conceptual design for a system that can perform 3G MAR across the broadest range of weights up to the max. lift capacity of the largest heavy-lift helicopter
   - Perform design trade-studies, as necessary, for the load train . . .
     - Helicopter, belly hook, overload protection, aero-grapple, pick-up line, parafoil & slider system

2. Reference mission CONOPS study
   - Perform an in-depth study of 3 reference missions
   - Develop preliminary cost estimate to execute each ref. mission
   - Consideration: Commercial service delivery is highly desirable

3. GN&C and autonomy study
   - Perform a trade study on systems and techniques that enable *efficient* and *reliable* helicopter-payload rendezvous and capture

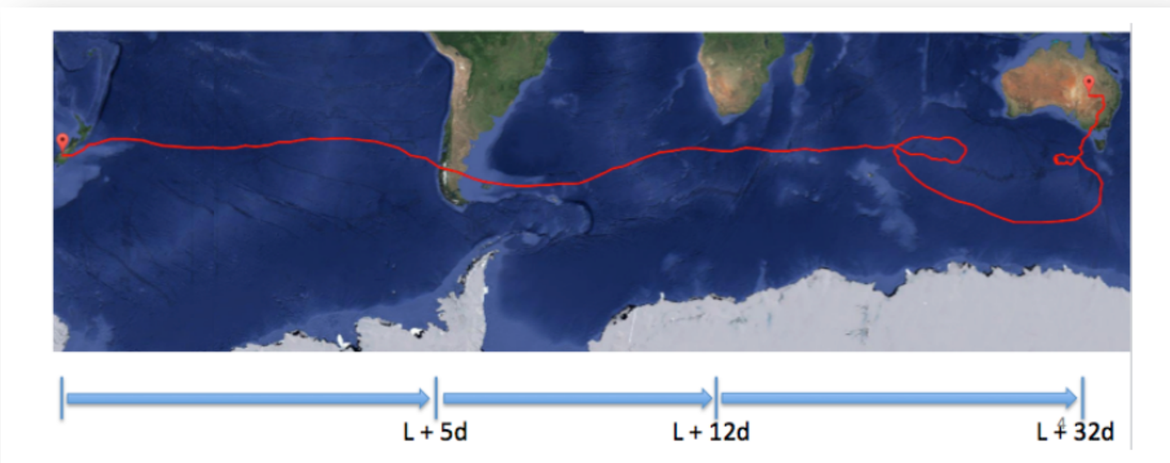


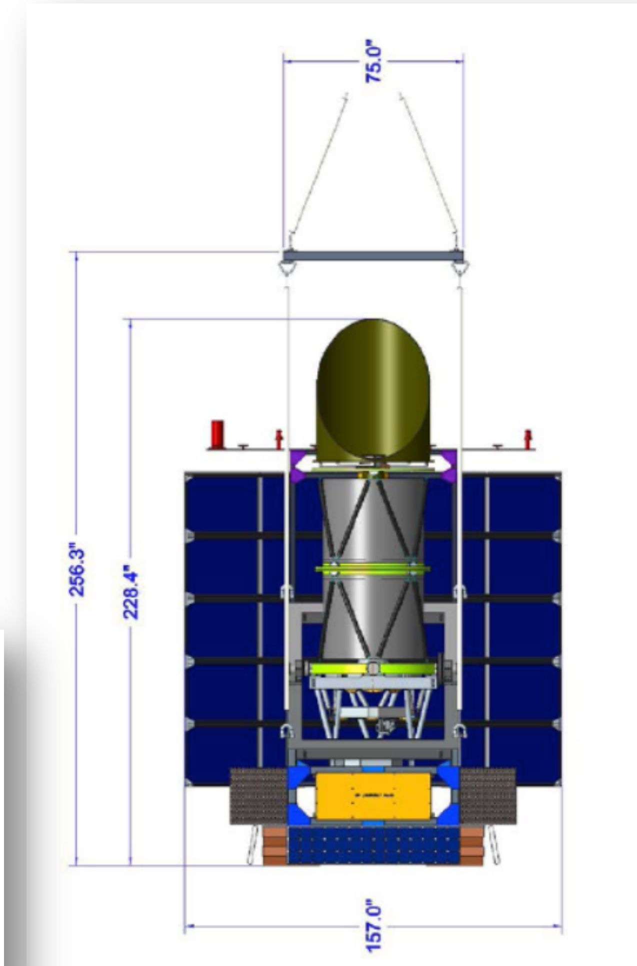
Reference Missions

- Goal was to select 3-5 reference missions to define the boundaries of the study
- Missions were selected that are enabled through or extended by the use of MAR
  - Mission "pull" desired
- 3 Missions were selected for the study
  - GHAPS
  - HULA
  - Vulcan "SMART Reuse"

GHAPS Reference Mission

- Gondola for High Altitude Planetary Science:
  - High-altitude, balloon-borne observatory
- Currently constrained to fly over land mass; proposed super-pressure balloon service to enable mid-latitude observations
- Critical descent recovery 50 NM west of Chile, over water - abort
- Land-based end-of-mission recovery in Australia
- Recovery ellipse within 50 NM of daily trajectory (abort)



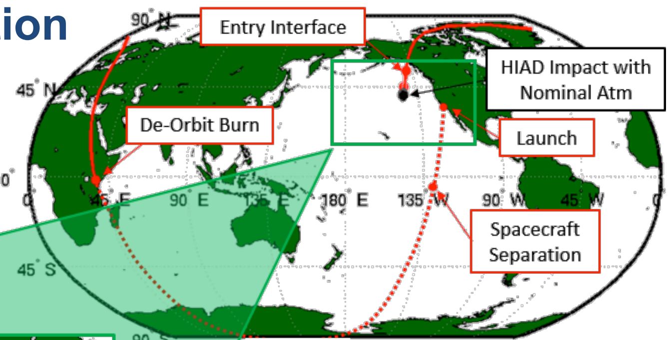


~3,400lbm

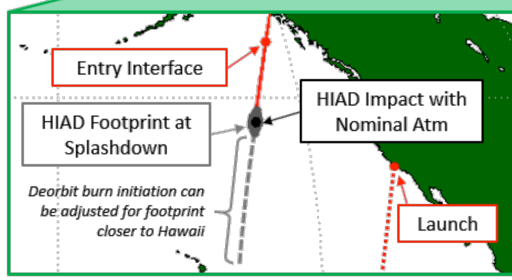
HIAD on ULA (HULA) Ref. Mission

Pursue Secondary Payload large scale flight demonstration to give NASA/ULA confidence in HIAD readiness.

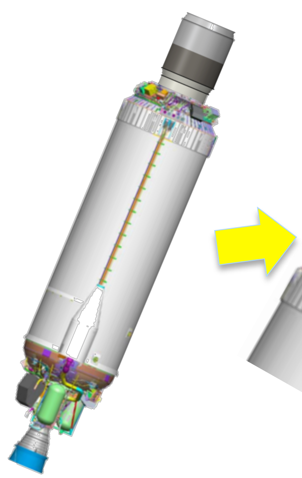
- Orbital reentry provides Mars relevant heating environment for HIAD technology.
- 5-6m scale is ~½ scale for both ULA booster recovery and proposed Mars EDL Pathfinder (both in 2024-2026 timeframe).
- Ballistic reentry; pointing, deorbit, and spin-up provided by ULA Centaur stage (simplifies reentry vehicle design and development effort).

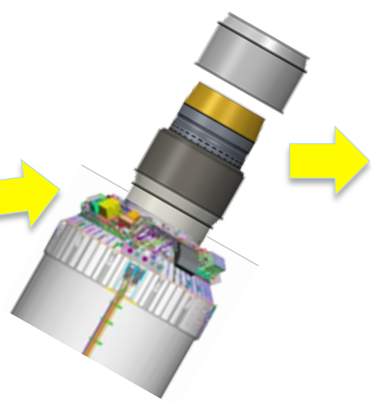


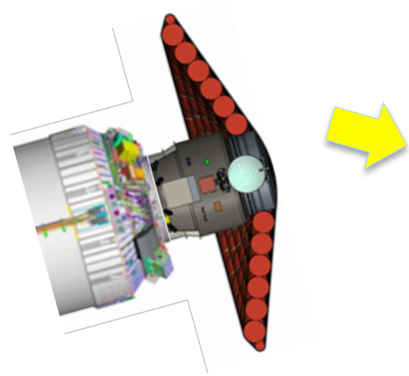
Ground Track (West Coast Launch)



Secondary Payload Footprint Analysis


Reentry Vehicle Stowed Config.


Separated Adapter

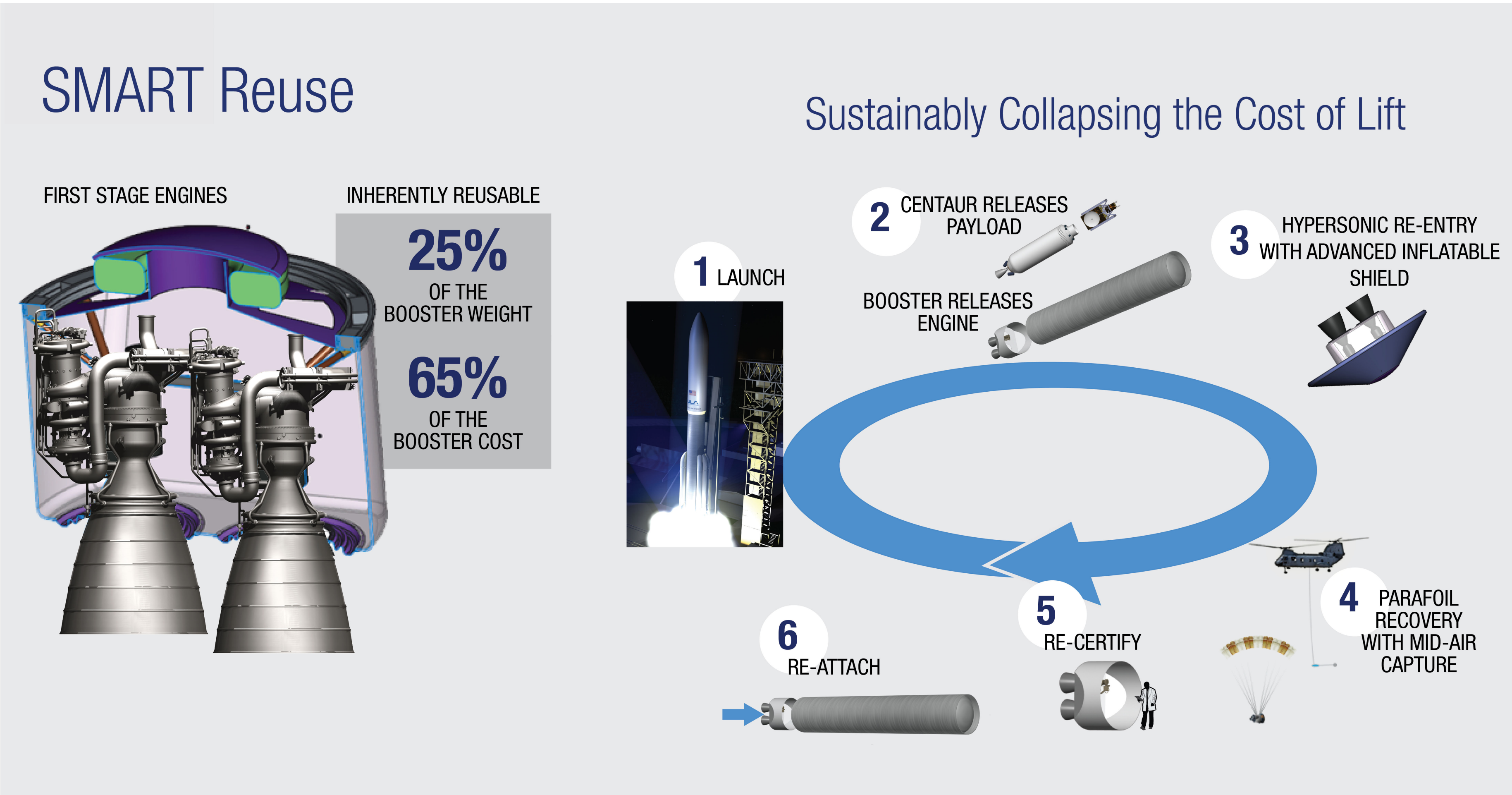

Deploy Aeroshell and Spin up for Entry

Reentry Vehicle


Mid-Air Recovery (MAR) Experiment End

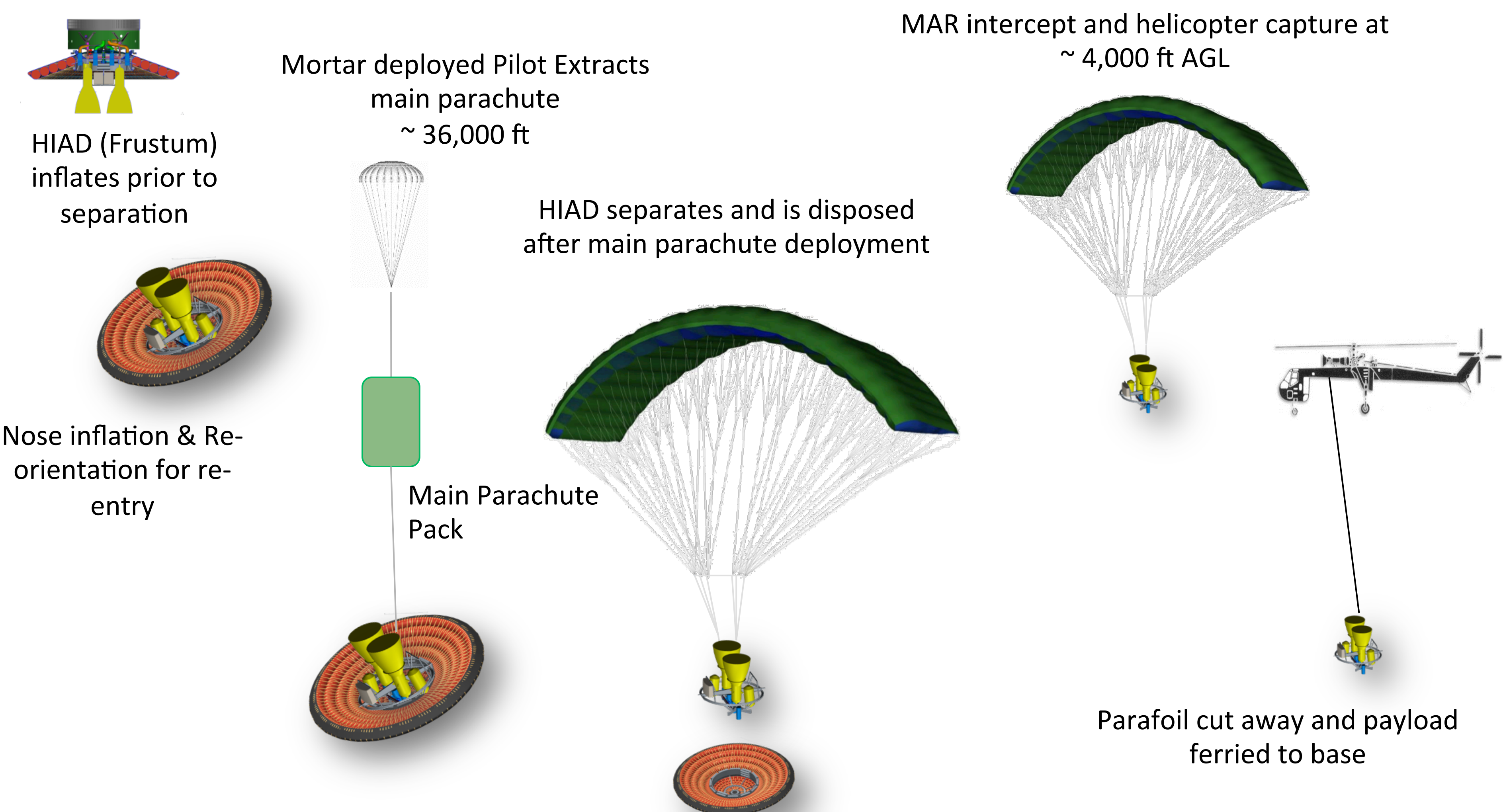
ULA Vulcan Reference Mission

- ULA's proposed Next Generation Launch System (*Vulcan*) to use "SMART" Reuse technology—Sensible Modular Autonomous Return Technology



(Image Used with Permission)

ULA Vulcan Reference Mission [2]



- Payload ~21,000lb
- Assume overwater recovery, start-of-ops (IIP is 1,000-2,000mi downrange)

Aero-Mechanical System Study

Partner: Airborne Systems®

Methodology:

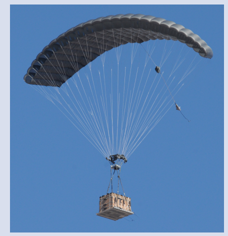
- Developed preliminary requirements
- Performed simple trade study on load train elements, and developed preliminary designs
- Performed loads analysis
- Developed technology development roadmap

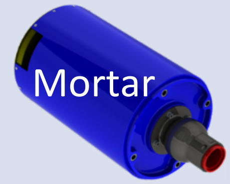
Findings: Aero-Mechanical Study

Ref Mission/Driving Requirements, Payload Mass ~4,000 and ~21,000 lbs.

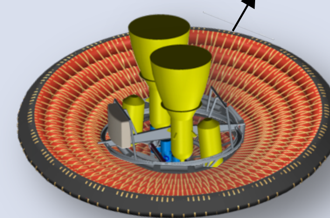
Parafoil Deployment

- Mortar deployed pilot chute at 36,000ft –HULA & VULCAN
- Pilot chute deployed main canopy at 35,000ft –HULA & VULCAN
- Pre-deployed drogue chute at ~100,000ft -GHAPS
- Drogue chute deployed main canopy at 35,000ft –GHAPS
- Main canopy released after grapple capture
- Parachute system used to deploy main parachute
- Parachute assembly weights ~10 lbs.





Mortar fired pilot flight path



Load Limiting Device

- Friction Braking System based on existing technologies and designs
- Prevents excessive load on the helicopter cargo hook
- Adjustable brake setting
- Helicopter Interface
- Grapple line releases if stroke is exceeded
- Some development required to adapt existing hardware to this application

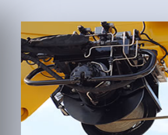
HULA & GHAPS, 3K to 8k lbf

Slip Clutch Friction Torque Limiter

High Performance Disc Brake

VULCAN, 20K to 40K lbf

Aircraft Braking System

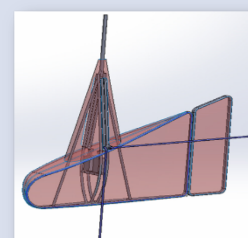


Constant Tension Winch System

MAR Grapple

- Utilizes 2 split flaps to provide lateral control, fore and aft positioning, and pendular motion damping
- Approximately 250 lbs. –HULA & GHAPS
- Approximately 400 lbs. -VULCAN
- Tubular Frame, Composite Aeroshell
- Designed for 2.0 x max design capture load, less than helicopter hook proof load

Original 1K Design



5K and 20K Conceptual Design

Findings: Aero-Mechanical Study[2]

Load Transfer Excursion Table

5K Helicopter: Bell 214 Capture Line Loads and Margins		14 CFR 29.865 External Cargo Proof Load lbs	14 CFR 29.303 External Cargo Utimate Load lbs			28-Apr-16 RAH
Design Factors	Helo External Cargo Hook Rated Capacity	Required Proof Load Factor 2.5	Factor of Safety 1.5	Realized Factors of Safety	Margins of Safety	Aero Grapple
	7,900	19,750	29,625.0			
Load Limiting Device	MAR Payload Weight	feet				
deceleration values	5,000	decel Stroke	Max starting Δv			Design Load
g's	Design Capture Load					2.0
0.30	6,500	18	18.6	4.6	3.6	13,000
0.50	7,500	18	24.1	4.0	3.0	15,000
0.60	8,000	18	26.4	3.7	2.7	16,000
1.00	10,000	18	34.0	3.0	2.0	20,000
2.00	15,000	18	48.1	2.0	1.0	30,000

- This table shows the range of functional successful LLD setups. The table will be optimized via analysis and test
- It is apparent that the likely range for decel g values will like fall in the 0.50 to 1.0 g range dependent on helicopter specifications and mission details
- The LLD design requirements will ensure a sufficient range of adjustment to meet future mission requirements

Concept of Operations Study

Partner: ERICKSON

Methodology:

- ID aircraft appropriate for load
- Pre-mission coordination requirements
- Deployment sequence
- Mission control hierarchy
- Communications requirements
- Mission scenarios and timelines
- Detailed cost estimates

Findings: Concept of Operations Study

Reference Mission	Aircraft	Deployment Logistics	Mission Profile	Steady State Mission Cost
GHAPS	Bell 214ST	Local lease, 2 locations	Land based, capture 50 nm off shore	$214k *($20M)*
HULA	Bell 214ST	Leased barge	Sea based, capture scenarios for 30 and 50 nm from barge	$223k *($M's)*
Vulcan	Erickson S-64F	Leased barge	Sea based, capture scenarios for 30 and 50 nm from barge	$250k *(65% of LV)*

Challenges
- Night Operations
- Target Rendezvous

Assessment: Feasible for daytime operations with appropriate guidance to target (beacon, radar, etc.)

GNC & Autonomy Study

Partner: DRAPER

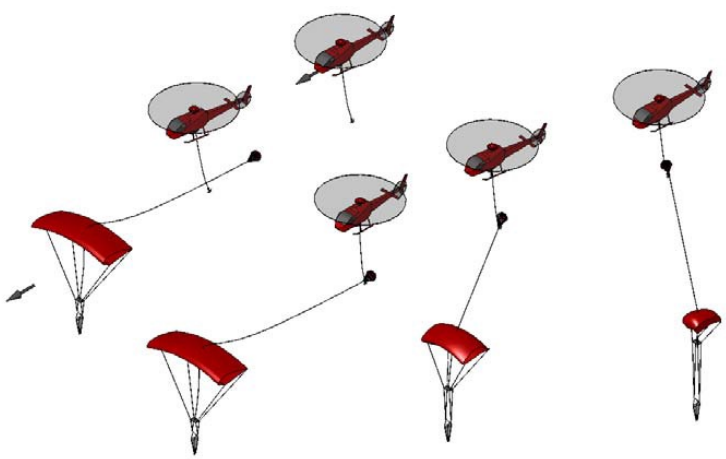
Methodology:

- Conducted a trade study and assessment of autonomous systems that could be leveraged to aid in reliable payload-helicopter rendezvous and capture.
- Each system assessed according its effect on the overall mission, which may include cost, launch weight, safety, speed, and other metrics
- The areas of autonomy and control investigated are parafoil control, autonomous intercept, and autonomous engagement

Findings: GNC & Autonomy Study

Baseline 3G MAR Mission:

Separation Distance	100+ nmi	100-20 nmi	20-1 nmi	< 1 nmi
Parafoil Guidance		Unguided - Slow Circle		
Parafoil Communication	Broadcast State at Low Rate			
Helicopter Communication	None			
Helicopter Guidance		Pilot Steers to Parafoil Location	Visual Acquisition	Manual/Visual Engagement
Events	Parafoil Deployment		Echelon Formation	Engagement, Pickup

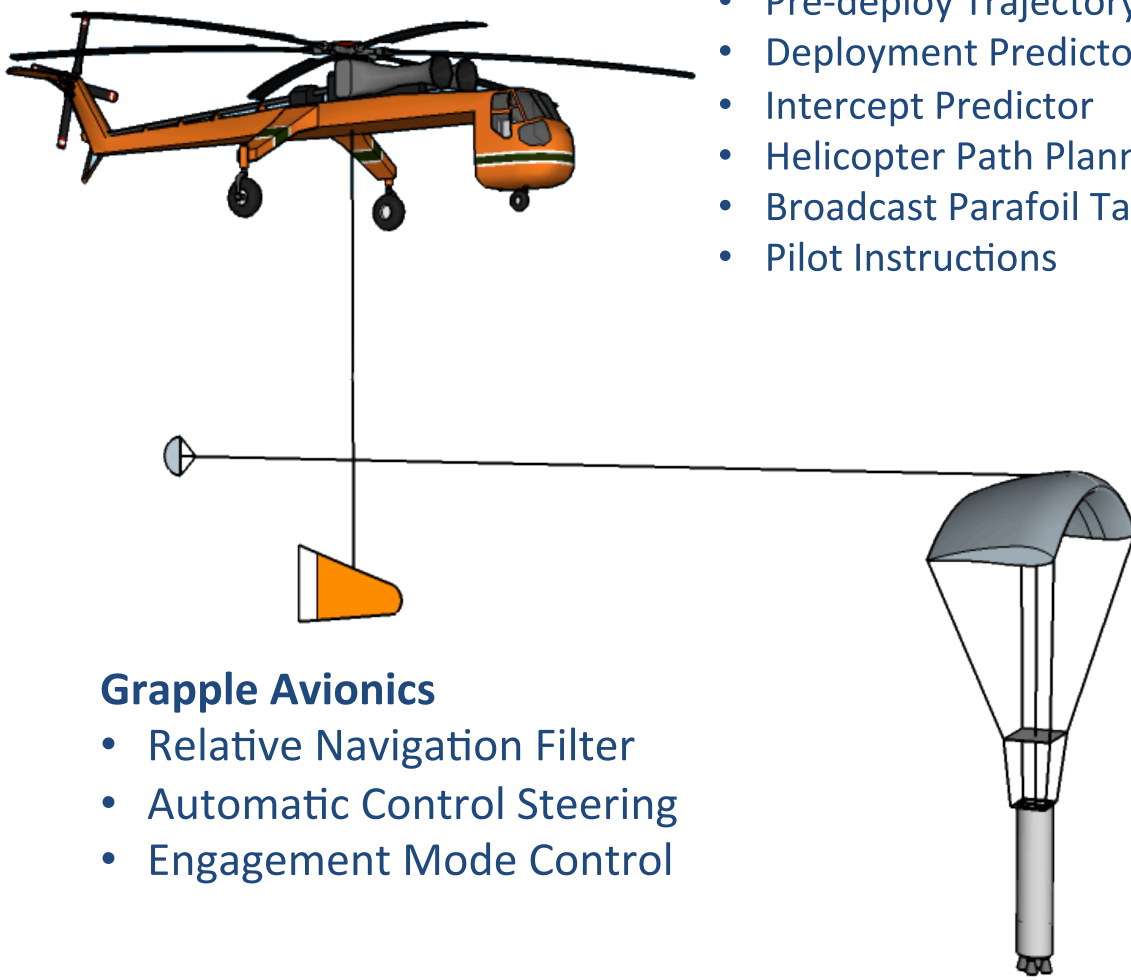


Airborne Systems 3G MAR

- Baseline 3rd Generation Heavy-Lift Mid-Air Retrieval does not require autonomy
  - *At minimum, need to know where payload is located to steer helicopter to intercept*
  - *Burden of recovery is on pilot and crew from visual acquisition to capture line engagement*
- Automated planning, control, and guidance can enhance 3G MAR

Findings: GNC & Autonomy Study

Automated Mission:



Helicopter Onboard Avionics
- Pre-deploy Trajectory Modeling
- Deployment Predictor
- Intercept Predictor
- Helicopter Path Planner
- Broadcast Parafoil Target Updates
- Pilot Instructions

Grapple Avionics
- Relative Navigation Filter
- Automatic Control Steering
- Engagement Mode Control

Parafoil Aerial Guidance Unit
- Automatic Control of Parafoil
- Parafoil Aero/Wind Estimator
- Broadcast AGU State

Findings: GNC & Autonomy Study

Notional Automated Mission:

<table>
<tr><td>Separation Distance</td><td>100+ nmi</td><td>100-20 nmi</td><td>20-1 nmi</td><td>< 1 nmi</td></tr>
<tr><td>Parafoil Guidance</td><td></td><td colspan="2">Steer to Intercept Target</td><td>Point to Recovery Area - Straight Flight</td></tr>
<tr><td>Parafoil Communication</td><td colspan="2">Broadcast State at Low Rate</td><td colspan="2">Broadcast State at High Rate</td></tr>
<tr><td>Helicopter Communication</td><td colspan="3">Send Intercept Point Target Updates</td><td>Send Recovery Position Target</td></tr>
<tr><td>Helicopter Guidance</td><td>Recovery System Positioning</td><td colspan="2">Direct Pilot to Steer to Predicted Intercept Location</td><td>Direct Pilot Through Engagement Mode Transitions</td></tr>
<tr><td>Events</td><td colspan="2">Parafoil Deployment</td><td></td><td>Echelon Formation Engagement Pickup</td></tr>
<tr><td>Autonomy and Planning</td><td>-Trajectory Modeling
-Deployment Predictor</td><td colspan="2">-Parafoil Aerodynamics and Sensed Winds Estimator
-Intercept Predictor
-Automatic Control of Parafoil
-Helicopter Path Planner</td><td>-Helicopter/Parafoil Relative Navigation Filter (Vision Based)
-Automatic Control of Grapple
-Engagement Mode Control</td></tr>
</table>

Technology Development Roadmaps

Aero-Mechanical Technology Roadmap

Objectives

- Design Verification
- Flight Performance
- Deployment/reefing

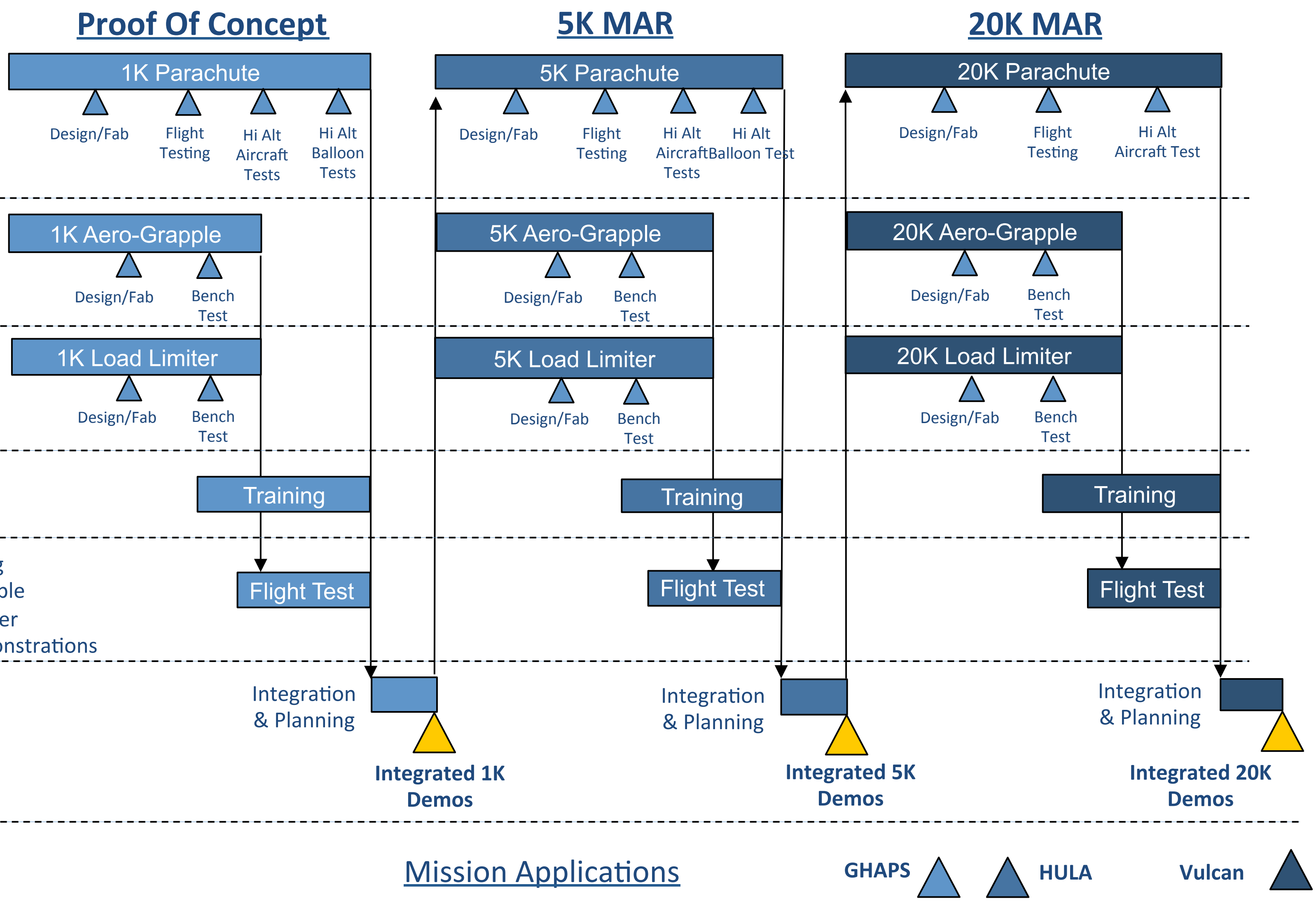
- Design Verification
- Performance
- Functionality
- Contingency ops

- Lightweight Design
- Performance
- Functionality

- Pilot/crew training
- Ops planning

- Pilot/crew flight training
- Flight test of Aero-Grapple
- Flight Test of Load Limiter
- Parachute release demonstrations

- Parachute deployment
- MAR captures
- Load limiter operations
- Parachute release
- Payload set-down



GNC & Autonomy Development Roadmap

Parafoil AGU Hardware

- **Interface COTS AGU to Payload**
  - Implement connections to payload avionics
- **Light-weight Control Design**
  - Create prototype bleed-air actuated parafoil
- **Light-weight Control Integration and Test**
  - Test campaign of bleed-air parafoil

Parafoil GNC

- **Parafoil System Identification Flights**
  - Flight tests to characterize dynamics
- **Simulation Development an GNC Design**
  - Adapt proven parafoil flight softwar
- **GNC Validation Flight Tests**
  - Checkout of software design

Helicopter Avionics Hardware

- **Communication Systems Development**
  - Integration of communication hardware and antennae to helicopter
- **Pilot Interaction Development**
  - Interface to existing cockpit hardware or development of new user interface

HLMAR Mission Planner

- **Pre-Deploy Trajectory Modeling**
  - Implement trajectory modeling software used by NASA mission
- **Parachute Deployment Predic**
  - Algorithm for planning optimal recovery staging
- **Helicopter Path Planner**
  - Software to utilize wind information to plan optimal path to intercept

Grapple Avionics

- **Vision Sensor Evaluation**
  - Test vision sensors in relevant environment to assess tracking ability
- **Relative Navigation Filte Development**
  - Utilize vision sensors for state estimation
- **Aero Grapple System Identification**
  - Flight tests to characterize grapple dynamics
- **Aero Grapple Controller Development**
  - Automated steering relative to parafoil

Summary & Conclusions

HLMAR Study Summary & Conclusions

- Aero-Mechanical
  - 1K MAR has been demonstrated and provides a basis for development of 5K and 20K systems
  - 20K is feasible and leverages mature/existing technologies and designs
  - Load limiting device is currently lowest TRL and requires development
- Preliminary cost estimates of MAR operation for 3 reference missions indicate that MAR is a small fraction of mission cost, with potentially large benefit
- Helicopter operations from seagoing barge will have to be examined more closely
- Technologies to automate the mission—helicopter, payload, aero-grapple—are mature/existing, may be critical to successful MAR

3G MAR is an application of existing/mature technologies, with some development and operational risks

Backup

Parafoil Control Trade

- Controlling heading of parafoil enables steering towards intercept point
- Trade study compared the following control methods
  - None: Parafoil rigged to fly in large circle, helicopter must find payload
  - Motors at Payload: Based on COTS guided parafoil systems that steer by deflecting trailing edge of parachute
  - In-canopy Actuators: New steering method in development that embeds motors inside parachute to open steering vents
  - Discrete Line Control: Start with deflected trailing edge and let out line to turn. Requires less power, but once line is let out parafoil cannont turn.
- Example trade matrix weights all metrics evenly and recommends COTS-based 2 actuator system

Control Method	Weight (lbs)	Redundancy (1-4)	Technology Readiness Level	Development Cost (1-4)	Mission Performance (1-4)	Overall Score (1-4)
None	0	1	6	4	1	2.8
2 Motors at Payload	~100	3	6	3	4	3
1 Motor at Payload	~50	1	5	2	4	2.4
In-canopy Servos	~20	4	4	1	3	2.6
Discrete Line Control	~20	3	2	1	2	2

Autonomous Mission

Separation Distance	100+ nmi	100-20 nmi	20-1 nmi	< 1 nmi
Parafoil Guidance		Steer to Intercept Target		Point to Recovery Area - Straight Flight
Parafoil Communication	Broadcast State at Low Rate		Broadcast State at High Rate	
Helicopter Communication	Send Intercept Point Target Updates			Send Recovery Position Target
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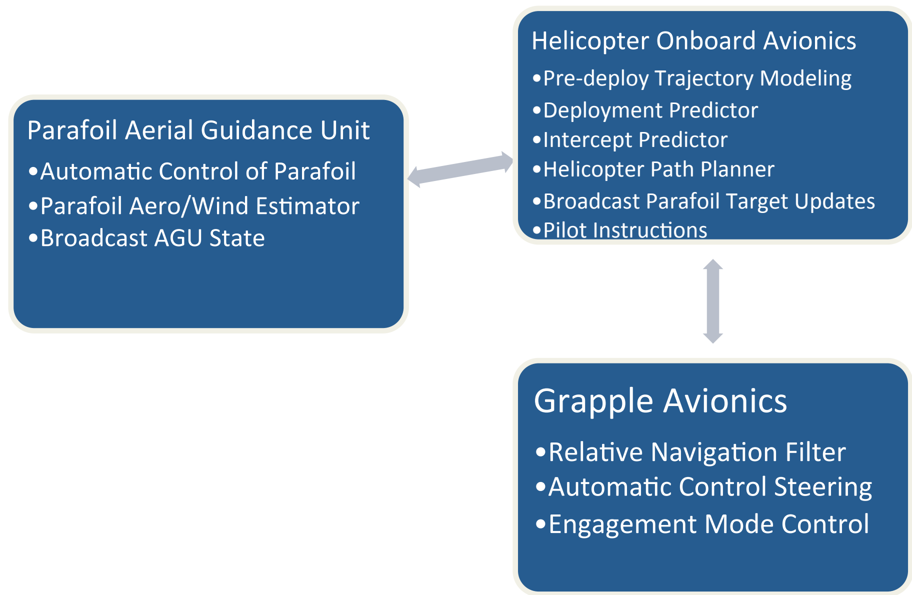
Events	Parafoil Deployment		Echelon Formation	Engagement Pickup
Autonomy and Planning	-Trajectory Modeling -Deployment Predictor	-Parafoil Aerodynamics and Sensed Winds Estimator -Intercept Predictor -Automatic Control of Parafoil -Helicopter Path Planner		-Helicopter/Parafoil Relative Navigation Filter (Vision Based) -Automatic Control of Grapple -Engagement Mode Control

- Autonomy can be added to the mission by developing a combination of these 3 technologies
  - *Parafoil Aerial Guidance Unit adds autonomy to the payload*
  - *Helicopter Onboard Avionics adds planning and pilot direction to the cockpit*
  - *Grapple Avionics adds autonomy to the engagement mechanism*

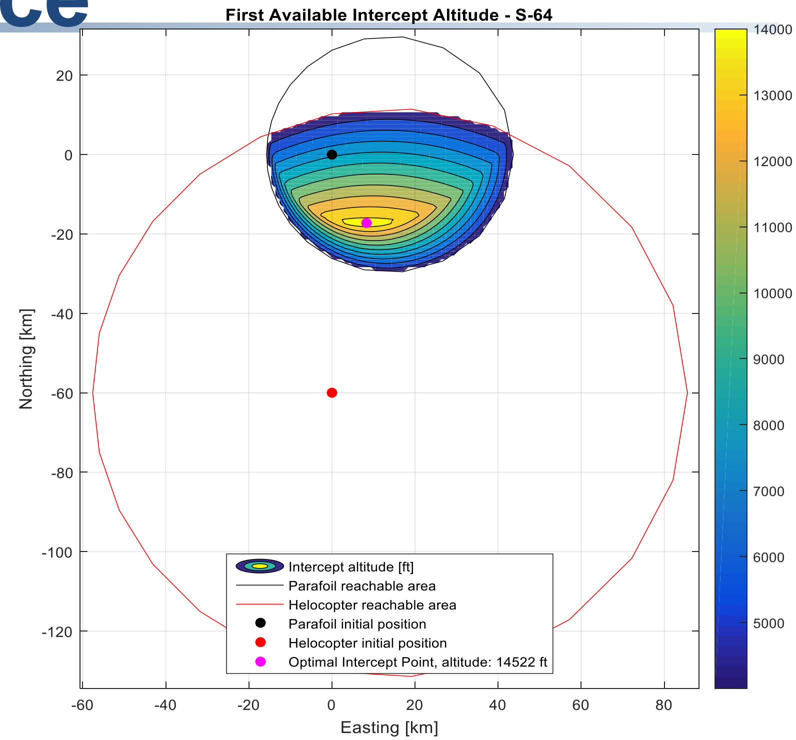


Autonomous Intercept - Communications

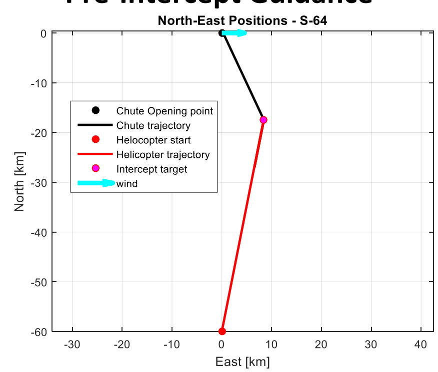
- Automating the intercept portion of 3G MAR requires communication between the payload and helicopter
- Potential Communication Methods
  - Automatic Dependent Surveillance – Broadcast (ADS-B)
    - Standardized direct communication between aircraft at 1 Hz with extensive commercial support
  - Iridium
    - Utilizes constellation of 66 active satellites to give global coverage for sending short data bursts every 6-22 seconds
  - Radio Modem
    - Customized data link for line-of-sight, high rate communications
- Helicopter Crew Interface – Used to give directions to pilot and crew
  - Visual Cue Display
    - Integrate intercept instructions into existing cockpit displays or head-up display
  - Synthetic Voice Prompts
    - Use text-to-speech module to send directions over VHF air band radio

Findings: Autonomous Intercept— Planning and Guidance

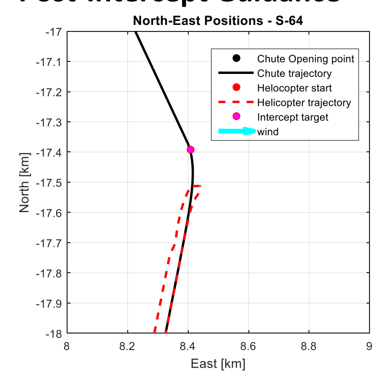
- Mission Planning can enhance 3G MAR performance
  - *Plan and Predict pre-deployment trajectory*
  - *Optimize staging area of recovery equipment*
  - *Optimize intercept point*
  - *Provide expected trajectories and event timelines*
- Mission Planning Inputs
  - *Model of pre-deployment trajectory*
  - *Real-time updates of system position, velocity, and attitude*
  - *Wind knowledge from forecasts or direct measurements*
  - *Parafoil flight characteristics updated during flight*
- Parafoil-Helicopter Guidance
  - *Calculate optimal intercept point*
    - In example at right, defined as earliest available meeting point inside reachable set of each system
  - *Guide both systems to intercept point*
  - *Steer parafoil towards recovery area while helicopter begins engagement*



Pre-Intercept Guidance



Post-Intercept Guidance



Autonomous Engagement

Echelon Formation
- MAR Helicopter moves into a left trailing formation with MAR parafoil

→

Advance
- Helicopter moves forward until the Grapple is midway between the capture line drogue and parafoil trailing edge

→

Contact
- Helicopter slides to the right until the Aero Grapple cable is in steady contact with the Capture Line

→

Capture
- Helicopter climbs slowly until the Capture Line is "captured" by the Aero Grapple

→

Pickup
- Helicopter continues slow climb until directly over the leading edge of parafoil as span slowly decreases

- Proximity Operations
  - *A precise relative navigation system can be used to off-load burden of visual tracking by crew*
  - *Optical Tracking*
    - Cameras installed on grapple hook or helicopter belly can track relative state of grapple and helicopter or helicopter/grapple and parafoil
    - Optical correlator can match images to provide state updates
  - *2-D Lidar*
    - Once in Echelon Formation, a lidar range scanner on the grapple hook can provide distance to capture line
- Grapple Control
  - *Swing Stabilization*
    - Use relative nav filter or IMU on aero grapple to actively damp out swinging modes
  - *Automated Steering*
    - Assist in Contact stage by automatically steering grapple into capture line

Airborne Systems Aero Grapple